Luderer, G., Pietzcker, R. C., Kriegler, E., Haller, M., Bauer, N. (2012): Asia's role in mitigating climate change: A technology and sector specific analysis with ReMIND-R. - Energy Economics, 34, Suppl. 3, S378-S390

DOI: 10.1016/j.eneco.2012.07.022

Asia's Role in Mitigating Climate Change: A Technology and Sector Specific Analysis with ReMIND-R

Gunnar Luderer[+], Robert C. Pietzcker, Elmar Kriegler, Markus Haller, Nico Bauer[*]

Abstract.

We use the ReMIND-R model to analyze the role of Asia in the context of a global effort to mitigate climate change. We introduce a novel method of secondary energy based mitigation shares, which allows us to quantify the economic mitigation potential of technologies in different regions and final energy carriers.

The 2005 share of Asia in global CO_2 emissions amounts to 38%, and is projected to grow to 53% under business-as-usual until the end of the century. Asia also holds a large fraction of the global mitigation potential. A broad portfolio of technologies is deployed in the climate policy scenarios. We find that biomass in combination with CCS, other renewables, and end-use efficiency each make up a large fraction of the global mitigation potential, followed by nuclear and fossil CCS. We find considerable differences in decarbonization patterns across the final energy types electricity, heat and transport fuels. Regional differences in technology use are a function of differences in resource endowments, and structural differences in energy end use. Under climate policy, a substantial mitigation potential of non-biomass renewables emerges for China and other developing countries of Asia (OAS). Asia also accounts for the dominant share of the global mitigation potential of nuclear energy. In view of the substantial near term investments into new energy infrastructure in China and India, early adoption of climate policy prevents lock-in into carbon intensive infrastructure and thus leads to a much higher long-term mitigation potential.

[+] Corresponding Author

[*] Affiliation of all authors: Potsdam Institute for Climate Impact Research, Potsdam, Germany

1. Introduction

Stabilizing climate change at a level in line with the targets formulated by the international community will require a substantial reduction of greenhouse gas emissions relative to business-as-usual (IPCC, 2007). The recent scenario literature shows that in absence of climate policy further expansion of fossil fuel use would result in an increase of CO_2 emissions from energy and industry by a factor 1.6-5.4 by 2100 relative to year 2000 levels Fisher et al., 2007; Clarke et al., 2009; Edenhofer et al., 2010; Luderer et al., 2012).

In its 'Copenhagen Accord', the United Nations Framework Convention on Climate Change has adopted the target of limiting the increase in global mean temperature to 2°C (UNFCCC, 2009). This target implies a tight limit on the remaining budget of anthropogenic greenhouse gas emissions (Meinshausen et al., 2009). The majority of modeling studies that have considered climate change mitigation targets consistent with climate stabilization at 2°C arrived at 2050 emissions reductions of at least 50% with respect to 2005 levels, and long term emissions that are close to zero or negative at the end of the century (Clarke et al., 2009; Edenhofer et al., 2010). Clearly, emission reductions of this magnitude require a large-scale transformation of global energy systems and a massive expansion of low carbon energy technologies. With its substantial share of global emissions, Asian countries will play an important role in any effort to limit climate change.

Crucial research questions relate to the role of technologies in achieving climate targets (e.g. Nordhaus and Nakicenovic, 2011). What can individual technologies contribute to emissions reductions? What are the determining factors for their effectiveness in reducing emissions and how do these factors vary regionally? And which technologies carry the largest part of the mitigation effort? The answer to these important questions is complex, because the role of technologies for mitigating climate change is not determined by their individual characteristics alone. Rather it strongly depends on the entire mitigation pathway characterized by a portfolio of technologies deployed over time.

Integrated Assessment Models (IAMs) with a detailed representation of the energy-economic system cover the relevant dynamics, albeit many in a stylized form, and therefore are well suited for studying the role of technologies in achieving climate targets. This requires deducing their individual contribution to the mitigation effort from the model output. The most common method is to study deployment levels of low-carbon technologies under climate policy and make comparisons to baseline levels (e.g., van Vuuren et al., 2007; Calvin et al., 2009; Krey and Riahi, 2009; Edenhofer et al., 2010; Krey and Clarke, 2011; Luderer et al., 2012). This approach provides an assessment of the technologies supported by climate policy, but does not directly address economic efficiency and mitigation effectiveness. For an assessment of economic efficiency, some studies have considered scenarios in which the expansion of individual low carbon technologies is assumed to be restricted or unavailable (Krey and Riahi, 2009; Edenhofer et al., 2010; Luderer et al., 2012). Comparing mitigation costs in such technology constrained scenarios against scenarios with the full set of technologies available allows the modeler to derive the increase in mitigation costs that arises from the technology restriction. This cost markup provides a good indicator for the contribution of a technology to the economic efficiency in achieving climate targets.

A complementary approach would be to assess mitigation effectiveness, i.e. the contribution of a technology to emissions reductions. How can emission reductions be attributed to individual technologies? Although this question seems rather simple, there is no straight-forward way of quantification. The term "Stabilization Wedges" has been coined by Pacala and Socolow (2004), who claimed that the mitigation gap, i.e. the difference between baseline emissions and emission levels required to achieve climate stabilization, can be bridged by a combination of currently available technologies. While such technology wedges have now become a common tool for illustrating climate stabilization pathways to stakeholders and decision-makers (e.g. Edmonds et al., 2000; Placet et al.,2004; EPRI, 2007; IEA, 2010), we are only aware of a few studies in the peer-reviewed IAM literature that use technology wedges (Riahi and Roehrl, 2000; Riahi et al., 2007; Shukla et al., 2008).

A problematic aspect of the Pacala and Socolow approach is the implicit suggestion that mitigation scenarios can be constructed by adding up mitigation wedges, and that individual technology wedges can be used interchangeably. As mentioned above, however, the role of individual technologies cannot be assessed in isolation. Their contribution to emissions reduction is an emergent system property. Thus, any method of attributing emission reductions to technologies should be regarded as a diagnostic tool for analyzing mitigation strategies for a given climate policy scenario, rather than a tool for constructing mitigation scenarios. Technology contributions are a function of each other and the mitigation scenario, and cannot be combined arbitrarily. This discussion reflects a fundamental tension between integrated assessment models of climate policy that decidedly take a systems perspective, and bottom-up approaches that try to combine individual mitigation potentials to marginal abatement cost curves (e.g. McKinsey & Company, 2009).

In this paper, we want to take the concept of attributing emissions reductions to individual technologies a step further while retaining a strict integrated systems perspective. We introduce a new method for attributing emission reductions as foreseen in mitigation scenarios from IAMs to individual technologies. This is a purely diagnostic tool for decomposing the mitigation effort. Due to the system dependency, the resulting mitigation shares per technology cannot be taken out of context and recombined to different mitigation scenarios. In order to avoid confusion with the popularized concept of mitigation wedges that has been used frequently in the latter way, we will call the fraction of emissions reductions attributed to a specific technology a "mitigation share" in the following.

The value of mitigation shares lies in synthesizing model output on the regional and sectoral (different secondary energy types) level into a coherent perspective of the low-carbon transformation. In terms of mitigation effectiveness, the emission intensity of the replaced technology mix matters, which differs across regions (e.g. coal-intensive energy systems vs. energy systems with a substantial share of nuclear) and final energy types (e.g. electricity vs. transport fuels. Secondary energy based mitigation shares capture these heterogeneities in aggregating mitigation contributions of technologies. While the methodology is useful tool as a diagnostic tool for comparing different scenarios from a single model, it is important to note that its usefulness for comparing results across models is constrained by its strong dependence on model-specific properties, such as the resolution of technologies and energy carriers. Its application across models would require standardized output on energy conversion routes which has not yet been established.

The regional focus of the paper is on Asia and a comparison with other key emitting regions such as the USA and the European Union. A number of studies have analyzed mitigation potentials and emission reduction strategies in Asia (Jiang et al., 2000; Kainuma et al., 2003) or individual countries of Asia, in particular China (e.g., Jiang and Hu, 2006; Chen, 2005; Chen et al., 2007; Steckel et al. 2011) and India (Shukla et al., 2008). The focus of our study is to analyze climate change mitigation in the context of the global effort. We apply the newly proposed decomposition method to the AME scenarios from the integrated assessment model ReMIND to investigate the following research questions: What are the most significant mitigation technologies, and how does their emission reduction potential compare across different final energy types? How do realized mitigation potentials of technologies change with increasing stringency of climate policy? How do mitigation potentials and decarbonization strategies compare across regions within Asia and between Asia and the rest of the world?

We finally apply the model and analysis framework to explore if there is a benefit of early adoption of climate policies in Asia. Previous studies found that fragmented climate policy regimes result make mitigation targets more difficult to achieve (Clarke et al., 2009; Jakob et al., 2011). Bosetti et al. (2009) and Richels et al. (2009) showed that the anticipation of future binding climate targets in developing countries influences near-term investment decisions, thus avoiding high-carbon lock-ins. We approach the matter by contrasting scenarios with immediate adoption of climate policy by all world regions with a scenario in which Asian countries are assumed to delay climate policies until 2020.

Our paper is structured as follows: In the next section, the model and scenario setup are introduced. Section 3 describes the methodological approach for the calculation of secondary energy based mitigation shares, and how it is distinguished from other approaches of determining the contribution of technologies to mitigation. Section 4 presents results from global and cross-sectoral perspective. Region specific results for Asia are reported in Section 5, along with an analysis of the role of early climate policy action in Asia. A broader discussion of caveats to the use and interpretation of the methodology are discussed in Section 6, followed by a concluding summary of the paper.

2. Model and scenario setup

The Refined Model of Investment and Technological Development ReMIND in its version 1.3 is used for this study. It is a global Integrated Assessment Model that represents 11 world regions and considers the time horizon from 2005-2100. A detailed description of this model is available from previous publications (Leimbach et al., 2010), and the technical model documentation (Luderer et al., 2010).

ReMIND is composed of three components: (a) the macro-economic growth module that describes socio-economic developments and determines the economy's demand for final energy, (b) a detailed energy system module describing conversion pathways from various types of primary energy via secondary energy to final energy, and (c) a climate module that simulates the response of the climate system to anthropogenic emissions of greenhouse gases and other forcing agents. A key feature of the model is that all three components are solved in an integrated, intertemporal optimization framework, thus fully accounting for feedbacks between all components of the system (Bauer et al., 2008).

In particular in terms of its macro-economic formulation, REMIND-R resembles well-known energy-economy-climate models like RICE (Nordhaus and Yang, 1996) and MERGE (Manne et al., 1995). REMIND-R is characterized by a comparatively high technological resolution on the supply side of the energy system (70 conversion technologies with detailed vintage structures), the consideration of technological learning in the energy sector, and the representation of trade relations between regions. This results in a high degree of where-flexibility (abatement can be performed where it is cheapest), when-flexibility (optimal timing of emission reductions and investments), and what-flexibility (optimal allocation of abatement among emission sources) for the mitigation effort.

AME scenario name	**Description**	**Short descriptor**
Reference	Reference Scenario. No climate policies beyond Kyoto Reductions for EU and Japan	**REF**
CO_2 Price \$10 (5% p.a.)	CO_2 pricing scenarios with globally uniform tax starting from 2015 increasing at a rate of 5% p.a. 2020 price levels are \$10, \$30, \$50, respectively.	**TAX-10**
CO_2 Price \$30 (5% p.a.)		**TAX-30**
CO_2 Price \$50 (5% p.a.)		**TAX-50**
3.7 W/m^2 NTE	Stabilization scenarios aiming at radiative forcing at 3.7 W m^{-2} (550ppm CO_{2e}, not-to-exceed), and 2.6 W m^{-2} by 2100 (450ppm CO_{2e}, overshooting allowed)	**3.7NTE**
2.6 W/m^2 OS		**2.6OS**
	Variant of TAX-30 scenario with Asian developing countries myopically following reference scenario until 2020. Asia adopts carbon tax in 2025, all other world regions in 2015.	**delay2020**

Table 1: Description of reference and climate policy scenarios used. REF, TAX scenarios, as well as 3.7NTE and2.6OS are part of the harmonized scenarios set of the AME study. delay2020 is a complementary scenario conducted for this paper.

The scenarios used for this study (Table 1) are based on the harmonized scenario set used for the AME intercomparison exercise comprising of one reference scenario, three scenarios with a prescribed global carbon tax, and two climate stabilization scenarios (Calvin et al., this issue). For the tax scenarios, the revenues are redistributed to the representative households, and thus are available for consumption or savings.

Many Asian countries have already adopted climate mitigation measures. In order to test the value of early adoption of climate policy, we prepared a variant of the TAX-30 scenario as an addition to the standard AME scenarios. In this (counter-factual) delay2020 scenario, the Asian macro-regions China, India, and other Asian developing countries are assumed to follow their business-as-usual trajectory without emissions pricing until 2020 and without anticipation of future climate policy, while all other world regions implement a uniform carbon tax already in 2015. The Asian regions are assumed to adopt the globally uniform tax from 2025 onwards.

3. Secondary energy based mitigation shares

3.1. Description of methodology

This section describes the methodology of secondary energy based mitigation shares used in this paper. A full documentation of the methodology is provided in supplementary material. The basic rationale is to consider climate-policy-induced changes in the technology portfolio for each region, time period, and secondary energy type, and to attribute emission reductions to individual energy conversion technologies. The method is unique in the sense that it tracks substitutions within the energy sector at the finest resolution represented in the model. It is composed of six distinct steps (the indices for region *r* and time *t* have been omitted for better readability):

1. For each technology *i* and secondary energy type *j*, calculate the difference of production between baseline and policy scenario ΔS_{ij} :

$$\Delta S_{ij} = S_{ij}^{\mathrm{pol}} - S_{ij}^{\mathrm{bau}}$$

2. Calculate emission intensities ε_{ij} for each technology *i* producing secondary energy carrier *j*:

$$\varepsilon_{ij} = \frac{E_{ij}}{S_{ij}}$$

   where E_{ij} are the emissions caused by the technology. In the case of joint production, emissions for each technology are distributed across products according to the relative shares of energy output.

3. Calculate the average emission intensity $\overline{\varepsilon}_j$ of replaced production of secondary energy carrier j:

$$\overline{\varepsilon}_j = \frac{\sum_{i:\Delta S_{ij}\leq 0}(E_{ij}^{\mathrm{pol}} - E_{ij}^{\mathrm{bau}})}{\sum_{i:\Delta S_{ij}\leq 0}\Delta S_{ij}},$$

   where the sums run over all technologies with deployment ΔS_{ij} lower than in the baseline.

4. For all conversion technologies i that are deployed at higher levels than in the baseline, calculate mitigation contribution M_{ij} for the production of secondary energy carrier j:

$$M_{ij} = \begin{cases} \Delta S_{ij}(\overline{\varepsilon}_j - \varepsilon_{ij}) & \text{if } \Delta S_{ij} > 0 \\ 0 & \text{if } \Delta S_{ij} \leq 0 \end{cases}$$

   The mitigation contribution is assumed to be zero for technologies with deployment lower than in the baseline. Note that M_{ij} will be positive for all technologies with emission intensities ε_{ij} smaller than the average emission intensity of the replaced technologies. This is usually the case, since climate policy will result in expansion of low emission technologies. The technology-specific emission intensities can differ between baseline and policy cases, e.g. because of different vintage structures. As explained in detail in the supplementary material, an additional term arises in this equation, if ε_{ij} in the policy case is different from the baseline value. Since this contribution is very small, and for the sake of conceptual clarity, we omit it here.

5. For each secondary energy carrier j, calculate the contribution of adjustments in energy end-use to emission reductions. These terms capture both the reductions in final energy demand and substitutions between final energy carriers.

$$M_j^{\mathrm{end}} = -\sum_i (S_{ij}^{\mathrm{pol}} - S_{ij}^{\mathrm{bau}})\overline{\varepsilon}_j$$

   Note that M_j^{end} can become negative if the secondary energy demand j is higher in the policy case than in the baseline. For some of the scenarios considered, we find electrification of energy end use to result in higher electricity consumption than in the baseline, thus yielding a negative end-use share for electricity. In line with intuition, however, this is found to be smaller than the end-use related emission reduction from non-electric end use. As discussed in Section 3.2, the treatment of such substitutions on the end-use level is a key source of ambiguity in the methodology.

We can proof that the sum of all technology contributions M_{ij} and the end-use contribution M_j^{end} is equal to the difference of baseline and policy emissions (see supplementary online material). Hence, the decomposition of emission reductions into the above components is complete. An important feature of this approach is thus that the end-use contribution is calculated explicitly, rather than determined as the residual of the mitigation gap.

6. For 11 regions, 48 primary to secondary energy conversion technologies and 9 secondary energy carriers represented in ReMIND-R, steps 2 and 3 result in some 450 non-zero summands of individual reduction contributions for each time step. For the further analysis, we thus group these 'micro-shares' into different technology categories, final energy types, and region groups.

3.2 Relation to alternative approaches

A number of alternative approaches for calculating the economic mitigation potential of technologies have been used in the literature or are conceivable. The choice of methodology can have a strong influence on the resulting relative size of mitigation shares.

In view of differences in methodologies which potentially have a strong effect on the results, it is important to consider the advantages and disadvantages of the alternative approaches. In order to structure the discussion, it is helpful to distinguish between three types of energy system adjustments in response to climate policy: (a) substitution between secondary energy supply technologies (e.g. substituting nuclear for coal in electricity production), (b) substitution between different final energy carriers (e.g. using electricity instead of liquid fuels in transport), and (c) final energy demand reduction (e.g. more efficient appliances or insulation of buildings, or reduction of energy service demand). We thus propose to evaluate alternative methodologies based on their ability to capture the energy system transformation in terms of the substitutions and adjustments occurring in the model.

By choice of an accounting method, implicit assumptions about substitutions between baseline and climate policy case are made. Methods can thus be categorized according to their assumptions about substitutions. In many studies, the mitigation contribution is calculated based on changes in primary energy consumption, e.g. in Edmonds et al. (2000), and Riahi and Roehrl (2000). Such a calculation based on primary energy is problematic for several reasons. First, there is no unambiguous way of primary energy accounting (Lightfoot, 2007; Macknick, 2011; IPCC, 2011, Annex II). This ambiguity in primary energy accounting translates directly to ambiguity in the calculation of CO_2 emission mitigation contributions (cf. Supplementary Online Material). Secondly, climate policy will induce substitutions on the level of secondary energy production (e.g. by replacing electricity from coal with electricity from nuclear power), or on the level of final energy demand (e.g. by a switch from non-electric final energy demand in households and industry to electricity). Such substitutions will not necessarily result in a one-to-one substitution on the primary energy level. Thirdly, related to the second point, different secondary energy carriers have different conversion efficiencies and emission intensities. For accurate accounting how much each energy carrier contributes to reduce emissions it matters, for instance, if renewable energy replaces fossils in electricity production (where one unit of wind or solar primary energy replaces some two to three units of fossil primary energy), or to produce heat (where renewables and fossils have similar conversion efficiencies). This difference is not captured by primary energy accounting.

Secondary energy based economic mitigation potentials as calculated with our approach alleviate some of the problems associated with the primary energy based calculation. Much of the ambiguity associated with primary energy accounting is eliminated, because substitutions are tracked in terms secondary energy production in physical quantities. The approach also fully differentiates according to emission intensities of different secondary energy types. The contributions of final energy demand reductions is accounted for in terms of avoided emissions that would have occurred if the energy had been produced with the technology mix deployed in the baseline scenario. In principle, it would also be possible to calculate the efficiency contribution based on the carbon intensity in the policy scenario. However, this would result in abatement credits (i.e., emission reduction per unit of secondary energy produced) for zero-carbon technologies that exceed baseline emission levels, and thus would be implausibly high.

A key limitation and source of ambiguity in the approach is, however, the treatment of substitutions between final energy carriers, for instance increased use of electricity in lieu of gas or coal for industry which are treated in terms of secondary energy demand changes. If one energy carrier is expanded to substitute for another, a negative end-use mitigation share for the expanded FE carrier is calculated, and a positive end-use mitigation share for the FE carrier that contracts. The composite end-use contribution is then calculated as the sum of both end-use shares. It is important to note that this approach deviates from the paradigm of tracking substitutions according to the model mechanics. In the supplementary material section, the effect of using alternative approaches for treating negative end-use shares is explored and found to have a noticeable but moderate effect on the results. The treatment of changes in end-use crucially depends on the model representation of the demand side, thus limiting comparability of mitigation shares calculated for different models.

For a model with detailed representation of end-use, it would in principle be possible to calculate end-use based mitigation shares. This would involve the following steps: (i) identification of all possible energy service supply pathways from primary energy to secondary energy to energy service (e.g. conventional cars with petrol, conventional cars with biofuels, electric cars with renewables, electric cars with nuclear etc. for the provision of passenger transport), and their deployment differences between baseline and policy case, (ii) calculation of the emission intensity of energy service supply of all alternative supply pathways (e.g. in gCO2 per passenger kilometer), (iii) calculation of the baseline emission intensity for each energy service, (iv) calculation of the mitigation share of each energy supply pathway (micro-shares), and (v) aggregation of these micro-shares into reasonable technology groups to obtain aggregate mitigation shares. These steps would be analogous to our methodology of secondary based mitigation shares presented in Section 3.2. It is important to note, however, that the practicability of tracking a huge number of possible conversion pathways in a highly complex energy system is a crucial limitation of such an approach. Moreover, ad-hoc assumption would be required to split between the supply side contribution (e.g. renewable electricity instead of petroleum) and end use technology contribution (electric instead of conventional cars), which will always be to some extent ambiguous. This challenge is akin to the split between carbon intensity and energy intensity improvements in Kaya-type decomposition analysis (e.g. Ang , 2004). Since ReMIND does not have a detailed representation of energy services, such an extension is clearly beyond the scope of our paper, but it would be a worthwhile topic for subsequent research.

4. Economic mitigation potential of technologies

4.1 The global perspective

In order to achieve climate stabilization, emissions have to be reduced substantially compared to business-as-usual. The scale of this challenge is illustrated in Fig. 1. Under our baseline scenario, which describes a world without any climate policy, emissions from the energy system would more than double between 2005 and 2060, and slightly decrease thereafter. Driven by a nine-fold increase in gross world product between 2005 and 2100, the scale of the global energy system would reach almost 1200 EJ/yr in terms of primary energy use[1] (Figure 2). This increase is largely driven by an increase in coal use. Our medium tax scenario TAX-30 results in a climate forcing of 2.9 W m^{-2} by 2100, roughly consistent with the 2°C target. Global energy-related CO_2 emissions peak in 2020 and decline to negative net emissions by 2080.

Based on the methodology outlined in Section 3, the emission reductions performed relative to the baseline scenario can be attributed to the technology groups fossil fuel switch, fossil CCS, biomass without CCS, biomass with CCS, other renewables, nuclear, as well as improvements in end-use efficiency. This analysis reveals that the bulk of the mitigation effort is borne by bioenergy use with CCS (BECCS), non-biomass renewables, and end-use efficiency. It is important to note that the end-use share accounts not only for the improvements of demand side efficiency in using various final energy carriers, but also for the substitution from energy carriers that are less efficient or more carbon intensive to those that are more efficient and less carbon intensive, e.g. increased use of electricity instead of solids in households and industry. The share of end-use efficiency in total abatement is particularly high initially, and continues to contribute substantially to the mitigation effort throughout the century. The significance of biomass lies (a) in its versatility as primary energy carrier for transport fuels, electricity production, and non-electric secondary, and (b) in the possibility to generate negative net emissions using BECCS. For this study we assumed a resource constraint on the availability of bioenergy that

---

[1] Primary energy demand is expressed in direct equivalent terms, see IPCC (2011, Annex II) for a detailed discussion of primary energy accounting methods.

increases from 2005 deployment levels of 55 EJ to 200 EJ in 2050. With this constraint, the main contribution of biomass to emissions abatement comes from redirecting bioenergy feedstocks to BECCS conversion pathways, rather than the expansion of bioenergy production. ReMIND considers a variety of BECCS conversion technologies, ranging from biomass based internal gasification combined cycle power plants (Bio-IGCC), to biomass-to-liquid, bio-gasification, and biomass-based hydrogen production. Non-biomass renewables deployment is dominated by wind energy, solar photovoltaic, and concentrating solar power, all of which contribute substantially to the provision of carbon-free electricity in the climate policy scenario.

The expansion of nuclear energy and the introduction of fossil CCS contribute at a smaller scale, and their contribution declines in the 2nd half of the century. We assume a constraint on global uranium availability of 23 MtU_3O_8 [2], which limits the long-term deployment level of nuclear. Fuel recycling of uranium and the use of alternative nuclear fuels are assumed to be unavailable. The competiveness of fossil vis-à-vis carbon-free alternative technologies decreases with increasing carbon prices due to the significant residual emissions, thus making fossil CCS less attractive in the long term. Fuel switch (i.e. use of less carbon-intensive fossil fuels, e.g. natural gas in lieu of coal) only have negligible contributions to the mitigation effort. At the level of ambition considered here, fuel switch is unattractive due to the small emission reductions compared to advanced low carbon technologies.

The dominance of BECCS, other renewables, and end-use efficiency in global emission reductions is robust over the entire set of climate policy scenarios (Figure 1b). Their realized emission reduction potential increases with increasing climate policy ambition and carbon prices. The contribution of nuclear remains almost constant, largely due to the limited uranium resource. Similarly, the cumulated economic mitigation potential for fossils with CCS is similar across scenarios, because in the high carbon price scenarios higher and earlier deployment of CCS in the first half of the century is offset by lower deployment of CCS in the later decades. Fuel switch from coal to gas accounts for a small portion of

---

[2] This constraint is based on the values given in the 2009 “Red Book” (NEA, 2009). It excludes the extraction of uranium from sea water and assumes recovery factors of ~0.5 for undiscovered and unconventional resources.

emission reductions in the TAX-10 and 3.7NTE scenarios, but becomes increasingly insignificant for the more ambitious scenarios.

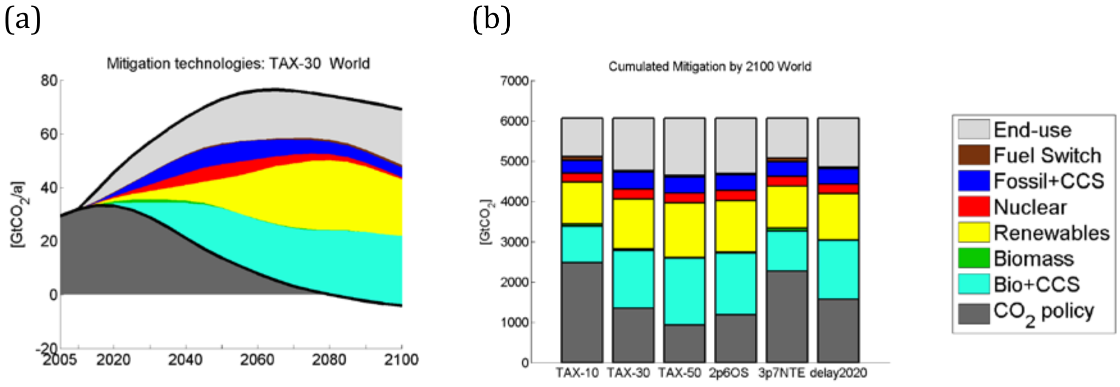

(a) (b)

Figure 1: (a) Emission gap between the baseline scenario and the TAX-30 climate policy scenario. The emission reductions induced by climate policy are decomposed into six technology groups as well as the contribution of changes in end-use. (b) Global emission reductions cumulated 2005-2100 for different climate policy scenarios.

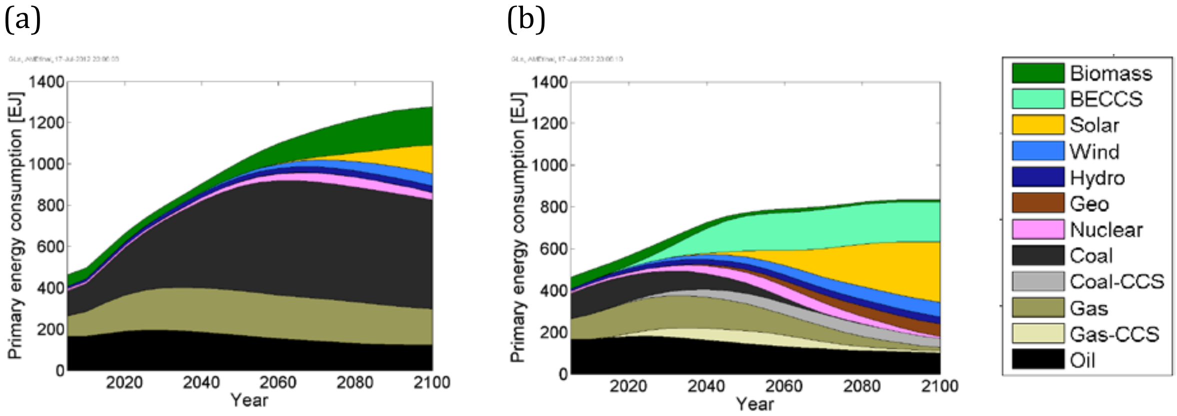

(a) (b)

Figure 2: Primary energy consumption (direct equivalent accounting) in (a) the baseline, and (b) the TAX-30 climate policy scenario.

Scenario	CO2 FF&I 2005-2100 $[10^3 \text{ GtCO}_2]$	GHG 2005-2100 $[10^3 \text{ GtCO}_2]$	Forcing in 2100 $[\text{W m}^{-2}]$	2100 GMT increase [°C]	Prob. of exceeding 2°C	Mitigation costs
REF	6.1	8.1	6.0	3.5 °C	100 %	-
TAX-10	2.5	3.8	3.7	2.5 °C	88 %	0.4%
TAX-30	1.4	2.5	2.8	2.0 °C	52 %	1.1%
TAX-50	0.94	2.0	2.5	1.8 °C	37 %	1.7%
3.7NTE	2.3	3.5	3.7	2.4 °C	78 %	0.6%
2.6OS	1.2	2.1	2.6	1.9°C	39 %	1.4%
delay 2020	1.6	2.7	3.0	2.1 °C	66%	1.0%

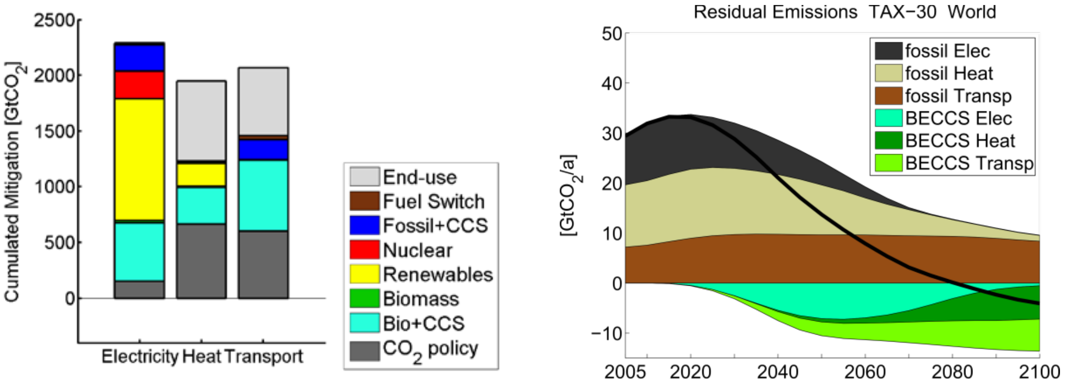
Table 2: Overview of scenario results in terms of cumulative CO2 emissions from fossil fuels and industry; cumulative emissions of CO2, N2O and CH4; anthropogenic radiative forcing (including long-lived GHGs, aerosols, and other forcing components); increase of global mean temperature relative to pre-industrial levels; and mitigation costs in terms of cumulated consumption losses relative to baseline discounted at 5%. A climate sensitivity of 3°C was used in the climate model for the estimation of GMT increase. The probability of exceeding 2°C is based on 2000-2050 cumulative CO2 emissions and calculated using lookup table provided by Meinshausen et al. (2009).

Table 2 provides an overview of the scenarios considered. The reference scenario results in a cumulated emissions budget from fossil fuel use of 6.0 TtCO_2 for the time horizon 2005-2100. An increase of radiative forcing to 6.0 W m^{-2} would result, with a transient temperature response of 3.5°C by 2100, assuming a climate sensitivity of 3°C. The carbon tax scenarios result in reductions of cumulated CO_2 emissions to 2.5 TtCO_2 (TAX-10), 1.4 TtCO_2 (TAX-30), and 0.94 TtCO_2 (TAX-50). Emission budgets for the climate stabilization scenarios 3.7NTE and 2.6OS are 2.3 and 1.2 TtCO_2, respectively. The tax scenarios lead to radiative forcing levels of 2.5-3.7 W m^{-2}. While three of the policy scenarios have a medium (TAX-30) or above 50% likelihood (TAX-50, 2.6OS) of reaching the 2°C target , the TAX-10 and 3.7NTE scenarios would likely fall short of this target.

The ordering of mitigation costs corresponds to that of emission budgets. The cumulated discounted consumption losses incurred by climate policy range from 0.4% (TAX-10), 0.6% (3.7NTE), to 1.1% (TAX-30), 1.5% (2.6OS), and 1.6% (TAX-50). A strongly convex cost pattern emerges: incremental mitigation costs increase substantially with increasing levels of climate policy ambition.

4.2 Decarbonization of end-use

The method of secondary energy based mitigation shares makes it possible to attribute the mitigation effort to the three final energy types electricity, heat, and transport fuels. In ReMIND-R, electricity is exclusively used for in the stationary sector, i.e. for residential, commercial and industry. The "heat" group of final energy carriers comprises all non-electric energy carriers for the stationary sector that are represented in the model: solids, liquids, gases, centralized and distributed heating, as well as hydrogen. Transport fuels considered are petrol, diesel, and hydrogen. Electrification of transport (e.g. electric vehicles) is not represented in ReMIND-R. In 2005, electricity generation worldwide accounted for emissions of 9.8 $GtCO_2$, while emissions from heat production (households and industry) and transport were 12.5 $GtCO_2$, and 7.2 $GtCO_2$, respectively[3].



(a)

(b)

Figure 3: (a) Mitigation contribution of technologies cumulated from 2005-2100, and broken down by the final energy types electricity, heat, and transport fuels for the TAX-30 climate policy scenario. (b) Residual emissions decomposed by end-use sector. The solid black line in (b) indicates net emissions.

Figure 3(a) breaks down emission reductions for the TAX-30 scenario by the final energy types electricity, heat and transport. The analysis reveals that mitigation contributions and decarbonization patterns differ considerably across these three different final energy types. An array of supply-side low-carbon alternatives is available for the power sector: renewables (mostly wind, photovoltaics and concentrating solar power), nuclear power, and CCS with fossils or biomass. As a consequence, cumulative emissions are reduced to 7%

---

[3] ReMIND 2005 data are calibrated to IEA Energy Balances (IEA, IEA, IEA 2007a, IEA, IEA, IEA 2007b)

of the emissions that would occur under business-as-usual. In ReMIND-R, much fewer technology options are both available and economic for non-electric energy, therefore heat and transport fuels account for the bulk of the residual CO_2 emissions from the energy system. In the transport sector, the production of synfuels and H_2 from biomass, and to a lesser extent also from coal, in combination with CCS are the most important mitigation technologies in our model. End-use (efficiency improvements and demand reduction) accounts for about a third of emission reductions relative to the reference scenario.

Heating is characterized by the highest share of residual emissions (35% of reference levels). The relevant supply-side mitigation technology options used by the model are methane and hydrogen production from BECCS, and non-biomass renewables for low-temperature heat. They combine to a reduction of 26% relative to reference levels. The dominant share of emission reductions (37%) in the heat sector originates from end-use: In addition to the reduction of energy intensity, the shift to electricity as a final energy carrier contributes strongly. Conversely, based on the emissions accounting methodology used here, the resulting increase of electricity demand yields a negative contribution of end-use for electricity.

The difficulty of decarbonizing heat and transport hints at a dominant role of these end-use types in defining the lower limit of achievable reduction targets ("feasibility frontier", cf. Knopf et al., 2011). Figure 3(b) provides a complementary perspective on sectoral emission patterns by decomposing residual fossil emissions and the negative BECCS contribution by end-use types. The fossil fuel emissions from the power sector are dominated by residual emissions from existing vintages of present generation capacities. These emissions decline gradually as old vintages of fossil-based power generation capacities are replaced by low-carbon alternatives. Fossil emissions from heat production remain substantial, and decrease only gradually in the 2nd half of the century, when an increasing share of the global bioenergy becomes available for this sector. Due to the lack of competitive alternatives, fossil fuel emissions from the transport sector remain above 2005 levels throughout the century, despite the considerable increase of carbon prices.

5. Climate change mitigation in Asia

5.1 Emissions abatement and technologies

Asia[4] accounted for 36% of global energy-related CO_2 emissions in 2005. In absence of climate policy, emissions are projected to increase more than three-fold over the course of the century, resulting in a 53% share of global emissions in 2100. The introduction of a price on carbon is found to result in a substantial decrease of CO_2 emissions (Table 3).

Scenario	CO_2 Fossil Fuel and Industry Emissions 2005-2100 [$GtCO_2$]				Asian share of global total
	CHN	IND	OAS	JPN	
REF	$1.47x10^3$	469	702	160	46%
TAX-10	603	249	258	76	48%
TAX-30	357	122	182	62	53%
TAX-50	262	85	141	58	58%
3.7NTE	568	225	254	74	49%
2.6OS	316	110	169	60	55%
delay2020	514	180	210	61	61%

Table 3: Overview of regional cumulative energy-related CO_2 emissions for the different scenarios.

Emissions trends in the reference scenario differ considerably across world regions, largely driven by differences in socio-economic developments, energy resource potentials, and patterns of energy end-use. Similarly, domestic abatement efforts and the role of technologies in realizing emission reductions vary according to regional specificities.

Figure 4 illustrates regional primary energy consumption in selected regions. Until mid-century, the bulk of the energy supply is provided by fossil fuels. China, India, Japan and USA are projected to rely heavily on coal, thus their energy systems are highly emission-intensive. By 2100, an increasing share of energy supply comes from wind, solar and

---

[4] In this study, we consider the four Asian regions China, India, Japan, and OAS (other developing countries of Southern, Eastern, and Southeastern Asia as well as Korea). We refer to the aggregate of these four regions as “Asia”.

biomass, particularly in the USA, China, OAS and other developing countries. When comparing 2100 China to India, the larger share of nuclear primary energy in India can be traced back to the model assumptions about higher import and transportation costs for coal in India compared to China, while the transportation costs for uranium are negligible. Under climate policy, fossil use is scaled back substantially in all world regions.

For the TAX-30 scenario, biomass and nuclear is expanded considerably compared to REF in 2050, and fossil-CCS is deployed at large scale. It is noteworthy that about four fifth of the global nuclear energy is projected to be deployed in Asia. By the end of the century, primary energy supply is dominated by renewables. Strong regional differences emerge in particular in terms of the role of solar energy, which has the highest resource potential in China, OAS, USA and other developing countries. Biomass use plays an important role in Russia (included in othIC), as well as Latin America and Africa (included in othDC).

As shown in Section 4.2, the sectoral structure of energy end-use affects technology options for climate change mitigation. Current patterns of final energy exhibit strong regional patterns (Figure 5): In 2005, the role of transport fuels in final energy use in the Asian regions is less significant compared to the USA and Europe. The share of electricity in end-use is comparatively small for developing countries. Based on our assumptions on at least partially converging final energy use patterns, we project increasing electrification and an increase in the demand for transport fuels in the developing world. The effect of climate policy on final energy is two-fold: First, it results in a substantial contraction of final energy demand in all world regions, and second it tends to increase the share of electricity in final energy use. This shift to electricity can be traced back to the large relative price increase of transport fuels and heat sources due to climate policies: Going from BAU to TAX-30, prices for natural gas and oil products at the end-user level increase by 100-400% in the second half of the century due to the carbon taxes, while average electricity prices only increase by 10-50%. These price differences are caused by the large number of decarbonization options for power supply, while the options for transport fuels or heat that are modeled in ReMIND are much scarcer (see Figure 3).

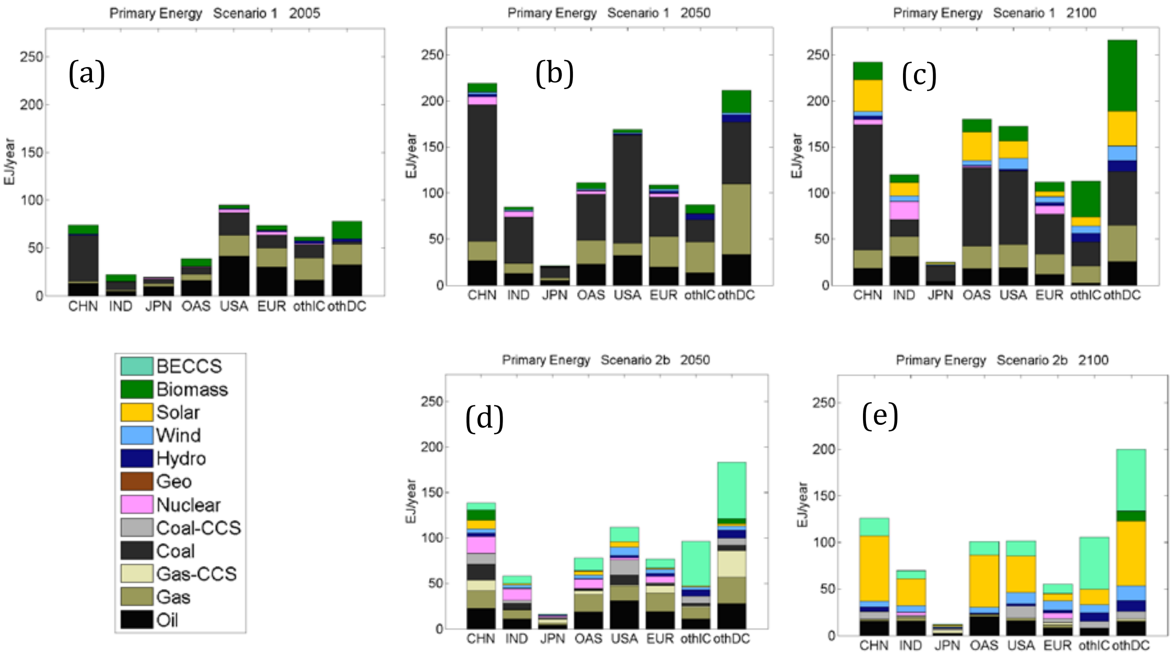


Figure 4: Regional PE mixes (direct equivalent accounting for nuclear and non-biomass renewables) for different world regions in 2005, 2050 and 2100. Upper row: REF scenario; lower row: TAX-30 scenario (othIC: other industrialized countries; othDC: other developing countries).

Figure 6 illustrates regional decarbonization patterns for the time span from 2005-2100, both in relative and in absolute terms. The reductions in cumulative emissions relative to BAU levels in the climate policy scenarios provide an indication of the economic mitigation potential. Under the TAX-30 climate policy scenario, global cumulative emissions contract to one fifth of the emissions that would occur under BAU. Regional abatement potentials vary strongly, with Europe and Japan reducing no more than 55% and 60% of BAU emissions, while other world regions (in particular biomass-rich Russia, Latin America and Africa) are almost carbon neutral over the course of the century. Renewable potentials, both biomass and non-biomass renewables, are found to be key drivers of regional decarbonization patterns. According to the renewable resource estimates used for ReMIND (Trieb et al., 2009) China features a high-quality solar resource potential, thus these technologies contribute strongly to emissions abatement. In India, by contrast, the resource potential of non-biomass renewables is currently estimated to be of lesser quality, making BECCS and end-use efficiency somewhat more important.

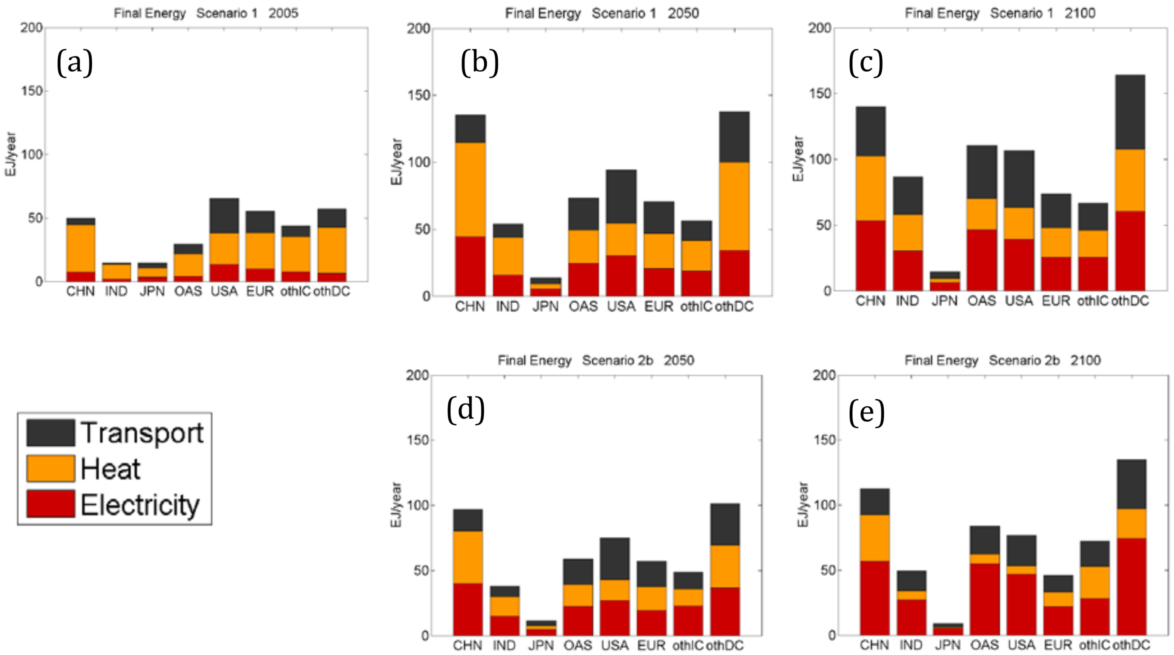


Figure 5: Regional final energy consumption by end-use types electricity, heat and transport for different world regions in 2005, 2050 and 2100. Upper row: REF scenario; lower row: TAX-30 scenario (othIC: other industrialized countries; othDC: other developing countries).

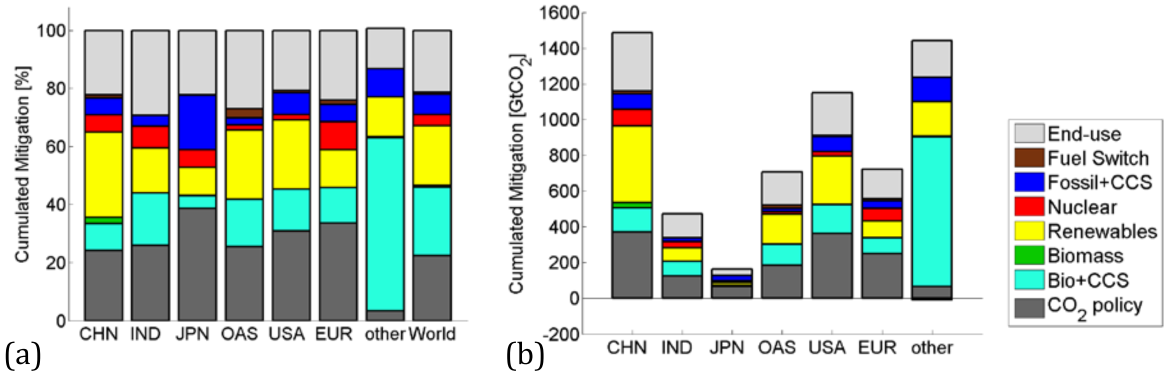


Figure 6: Cumulated mitigation from 2005-2100 in selected model regions, expressed (a) relative to baseline emissions, and (b) in absolute terms.

5.2 The significance of early action: Asian developing countries

The rapidly developing economies of Asia have recorded considerable increases of greenhouse gas emissions over the past years (e.g. Raupach et al., 2007). Our baseline projects a further rapid increase of emissions if no climate policy is implemented, due to continued economic growth, and a strong reliance on coal as a source of energy. In order to satisfy the growing energy demand, substantial investments into energy infrastructure are required. This is exemplified by the rapid expansion power sector as shown in Figure 7. In absence of climate policy, the bulk of the near term investments in China and India will go to coal-based installations. OAS is less coal-reliant in the near term, as it has cheaper gas reserves than India or China. In the medium term, the share of nuclear in investments increases substantially. Even without climate policy, investments in renewables are significant, and account for a dominant share of power sector investments by the end of the century. It is important to note, however, that the share of investments into renewables and nuclear tends to overstate their share in electricity production, since capital expenditure is much higher for these technologies than for fossil-based installations.

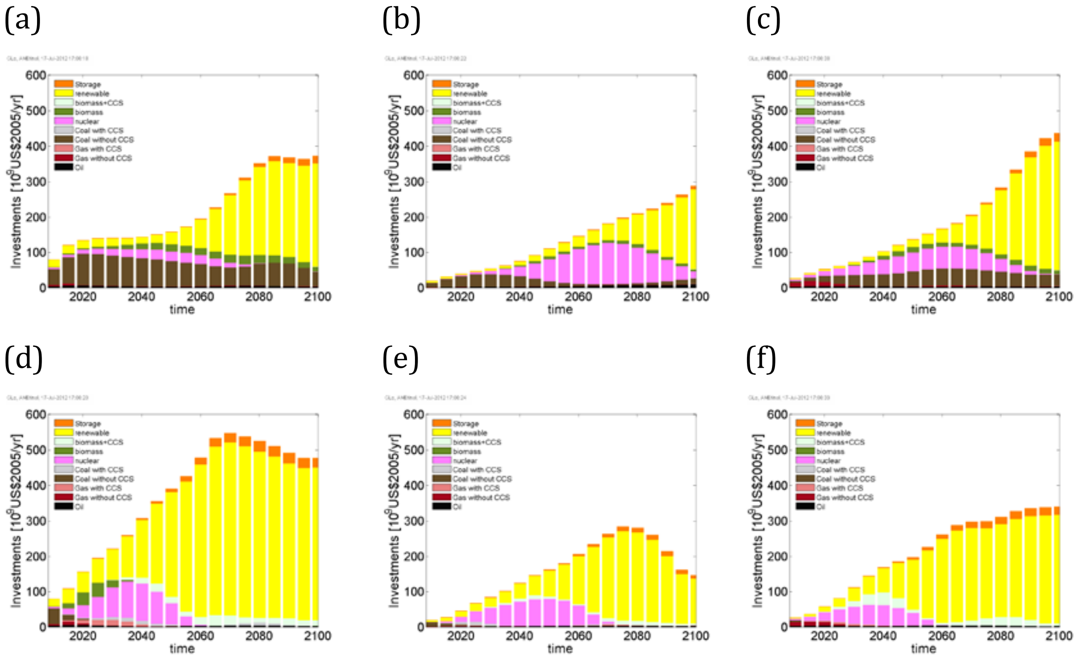


Figure 7: Investments into power generation capacities for China (left), India (middle) and OAS (right), for the reference case (top) and the TAX-30 climate policy scenario (bottom).

Climate policy has several effects on power sector investments. In both China and India, investments into conventional coal-fired power plants decline rapidly and vanish after 2020, as the carbon taxes quickly make electricity from coal uneconomic. In the medium to long-term, as the capital-intensive nuclear and non-biomass renewable technologies account for an increasing share of new installations, the overall scale of investments increases substantially. After 2070, renewable investments decrease due to a stabilization of electricity demand and limitations in the renewable resource potential. As coal is phased out and nuclear electricity is initially cheaper than that from renewable technologies, nuclear investments are brought forward in the climate policy case compared to the baseline. In the case of India, nuclear investments in the 2nd half of the century are smaller than in the reference case, due to a depletion of global uranium resources, and the increasing competiveness of wind and solar energy.

In view of the large investment needs in developing Asia, as well as the strong effect of climate policy on near-term investments the question arises to what extent near-term climate policy affects energy system emissions in the long-term. In order to contrast the short-term and long-term effects of early adoption of climate policy, we constructed a variant of the TAX-30 scenario ("delay2020") in which China, India, and other developing countries of Asia were assumed to delay climate policy and to follow the reference development myopically until 2020, while other world regions adopt the uniform carbon tax from 2015. The Asian regions are assumed to join the global climate mitigation effort in 2025 by adopting the carbon tax. Considering the substantial climate mitigation efforts that are already under way in Asia, it is important to note the assumption of no climate policy until 2020 presents an already counter-factual development. For instance, China's Copenhagen Pledges in terms of reductions of the emission intensity of GDP and the low-carbon share in primary energy provision are roughly in line with our TAX-30 scenarios. By contrasting our hypothetical delay2020 scenario with immediate adoption of climate policy in all world regions, we can not only analyze how near-term emissions decrease in response to climate policy, but also how early action influences the achievability of deep emission cuts in the medium to long-term future.

Figure 8 shows mitigation shares for both the TAX-30 and the delay2020 case for China, India, and OAS. Immediate adoption of climate policy results in a peaking of energy-related emissions in 2020 at a level of 7.2 $GtCO_2$ (China), or 2025 at a level of 1.9 $GtCO_2$ (India) and 3.0 $GtCO_2$ (OAS). For a delay in climate policy, the time of peaking remains unchanged for China and India, but emission levels in 2020 are 56% higher than in the case of China, 69% higher in the case of India, and 26% in the case of OAS.

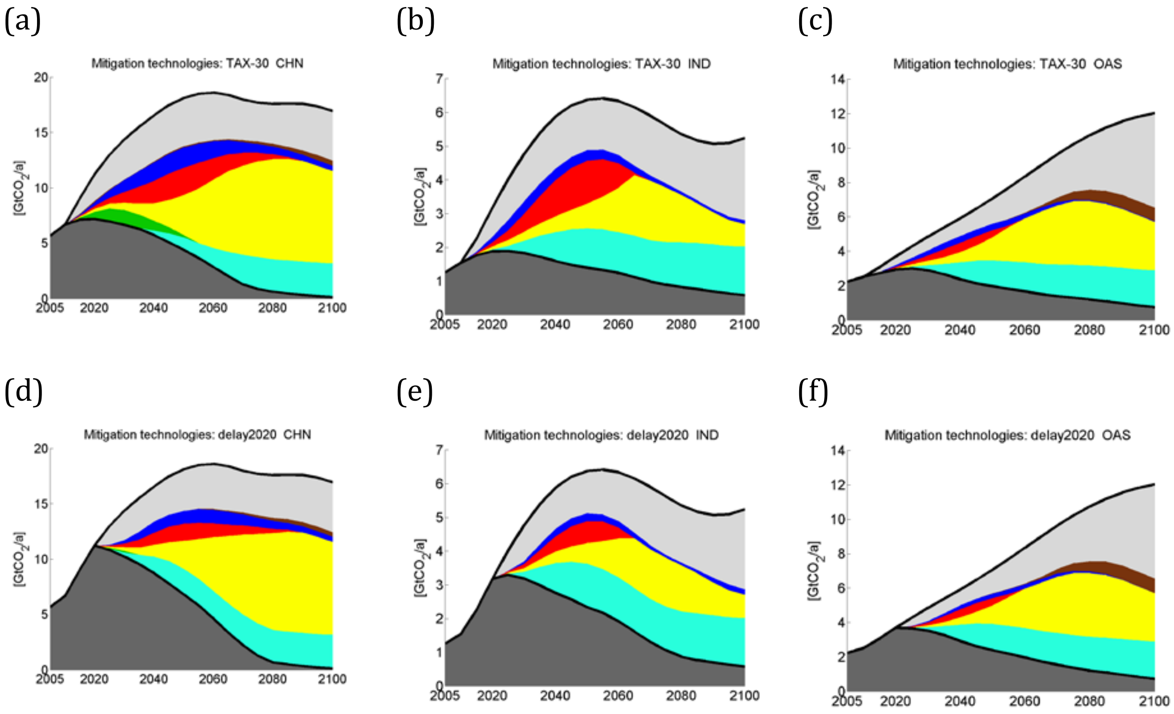


Figure 8: Emission reductions for China (left), India (middle), and other developing Asia (OAS, right) in response to the carbon taxation for the TAX-30 scenario (upper row) and the delay2020 scenario (lower row). Same color code as in Figure 1.

Due to the lock-in into carbon-intensive energy generation capacities, the effect of delay on long-term emissions is substantial[5]. For delay2020, emission levels in 2050 are still 1.9 GtCO$_2$ (China) and 1.1 GtCO$_2$ (India) higher, respectively, than in the TAX-30 scenario with immediate action. The emissions of China cumulated from 2005-2100 in the delay2020 case are 513 GtCO$_2$, roughly 44% higher than in TAX-30. In the case of India, the cumulative emissions amount to 180 GtCO$_2$, which corresponds to an almost 50% increase relative to TAX-30. For OAS, the effect of delay is less pronounced because the bulk of future emission growth in the no-policy scenarios is projected to occur after 2020. In the delay2020 case, the global CO2 emissions in 2020 are 7% higher than in the corresponding TAX-30 case, and the resulting increase of cumulative global CO2 emissions until 2100 amounts to 240 GtCO2. The 10-year delay of climate policy of Asian countries has a small but noticeable effect on

---

[5] One has to keep in mind that the effect of delaying climate policy is influenced by the assumption in ReMIND that power plants cannot be retired early.

long term radiative forcing and temperature levels. In particular, it implies an increase in the likelihood of overshooting the 2°C target to 66% compared to 52% in the TAX-30 scenario (Table 2).

6. Discussion: Methodological issues

The analysis of the role of technologies in reducing energy system emissions ranks high on the agenda of climate mitigation research in general and integrated assessment modeling in particular. As discussed in Section 1, different ways of characterizing the role of technologies in for climate change mitigation exist. They can be grouped into (a) analyses of deployment levels, (b) analyses of the cost markups arising from foregoing certain technology options ("knock-off scenarios"), and (c) analysis of mitigation effectiveness, i.e. the quantification of the contribution of technologies to emission reductions. In this paper, we introduced the concept of secondary energy based mitigation shares, which falls into the latter category.

While these three different approaches provide a consistent perspective, they are not equivalent. They assess the role of technologies from different angles, and thus are largely complementary. Studies of deployment levels can inform about technology roadmaps and expansion rates that are consistent with climate stabilization targets. Technology knock-off scenarios give an indication of the degree of indispensability of low carbon technologies, and allow quantifying their strategic economic value. Mitigation shares provide a metric for the contribution of technologies in terms of emission reductions achieved, i.e. the realized mitigation potentials. Deployment levels of mitigation technologies, by themselves, do not provide the full information about emission reductions induced, since these depend on the emissions of production capacities replaced. Thus the added value of mitigation shares as a diagnostic tool lies in weighting the expansion of each technology with the emission reductions induced by replacing secondary energy production capacities that would have been utilized in the absence of climate policy, thus synthesizing information about deployment levels in the policy case relative to the baseline, as well as substitutions within the energy system.

The most critical drawback in the use of mitigation contributions is the methodological complexity and ambiguity. A number of different approaches exist for quantifying emission reduction contributions of technologies. This ambiguity in methodology leads to uncertainty about the appropriate decomposition of emission reductions. In our view, the secondary energy based mitigation shares presented here are superior to existing approaches based on primary energy deployment, chiefly because substitutions of fossil-based technologies by low-carbon alternatives are traced at the finest level resolved by the model, and because they remove the ambiguity related to primary energy accounting. However, as discussed in Section 3.2, the treatment of substitutions between different final energy carriers remains ambiguous in this framework.

Several other important caveats and limitations remain: (a) in view of the complex system dynamics within the energy system, it is not possible to construct alternative mitigation scenarios by recombining individual mitigation shares. The decomposition of emission reductions into mitigation fractions is thus only a diagnostic tool for the analysis of individual climate change mitigation scenarios. This caveat is particularly important for the communication of results to stakeholders and policy-makers. (b) The method only accounts for expansion of mitigation technologies beyond baseline levels. Thus it tends to obscure the role of low-carbon technologies with substantial deployment levels in the reference scenario, e.g. nuclear and wind power. (c) The calculation of secondary energy based mitigation shares is rather complex and needs to be tailor-made to the representation of the energy supply and demand structure that is specific to each individual model. The model-dependence of the decomposition methodology limits its applicability for comparisons across models. Further research is required to explore how different energy system representations affect the outcome of the decomposition analysis.

7. Summary and conclusion

We have described the results of a reference and several climate policy scenario runs conducted with ReMIND-R. The focus of our analysis was on the economic mitigation potential of technologies, with a special focus on Asia.

A number of important policy-relevant conclusions emerge from our analysis: Firstly, we find that Asia plays a pivotal role in the global efforts to achieve climate stabilization. Asia currently accounts for almost two fifth of global emissions, and its share is projected to grow further, both in the reference and the climate policy scenarios. Clearly, without involvement of Asian countries, ambitious climate targets cannot be reached. Reconciling the legitimate priorities of Asian developing countries in terms of development and economic prosperity with the requirements of global climate change mitigation requires a substantial deviation from current emission trends and large-scale deployment of low-carbon technologies.

On the global scale, we find biomass in combination with CCS, other renewables, and the reduction of energy demand to offer the largest potential for economic CO_2 emission reductions. Nuclear and fossil CCS also contribute substantially to emission reductions, particularly in the medium term. We find substantial differences in decarbonization of different final energy types. While renewables, nuclear and CCS offer ample opportunities for reducing emissions from electricity supply, the mitigation options for non-electric energy demand represented in ReMIND-R (geothermal heat pumps, bioenergy, and price-induced improvements of energy intensity) only have limited reduction potential. Consequently, much larger emission reductions are realized in the power sector, and the bulk of residual emissions originate from the provision of transport fuels and heat energy supply. This result is in line with the findings of the RECIPE project (Luderer et al., 2012), and suggests that the further development of relevant mitigation options for non-electric energy demand (such as electric mobility, the thermal insulation of buildings, and bioenergy use) are of crucial importance for the cost and achievability of low stabilization targets.

Regional differences in the role of mitigation technologies can emerge from three different factors: (a) supply-side differences in fossil and renewable energy resource endowments; (b) demand-side differences in the current structure and the future development of final energy use; and (c) differences in technology factors, such as capital costs, labor costs, and the policy environment, e.g. due to subsidies, regulation, and public acceptance. In our scenarios, differences in resource endowments result in considerable regional differences in technology deployment. While the biomass resource potential and fossil fuel resources are limited in Asia, other renewables are an important long-term mitigation option for China, other developing Asia, and, to a lesser extent, India. In the medium term, nuclear contributes sizably as a bridging technology under climate policy. So far, systematic studies of the effect of structural changes in energy end use, as well as the effect of differences in technology factors are missing. Such analyses should be a priority for further research.

Finally, our results emphasize the long-term benefits of early implementation of climate policy. Many countries in Asia have already adopted climate policy measures. We performed a stylized analysis that contrasts the scenario with immediate and globally coordinated climate policy to a scenario of delayed participation of Asian developing countries. Our results demonstrate that early adoption of climate policy does not only result in near-term emission reductions, but also avoids lock-in into carbon intensive infrastructure and thus leads to a much higher long-term mitigation potential, in particular in China and India.

Acknowledgements: We would like to thank participants of the AME meeting in Xian as well as two anonymous reviewers for their comments on this work, which helped to improve the methodological framing of this paper. The participation of the ReMIND team in the AME project was supported by EuropeAid under the Climate Policy Outreach (CPO) project.

References

Ang, B., 2004. Decomposition analysis for policymaking in energy: which is the preferred method? Energy Policy 32 (9), 1131 – 1139. http://www.sciencedirect.com/science/article/pii/S0301421503000764

Bauer, N., Edenhofer, O., Kypreos, S., February 2008. Linking energy system and macroeconomic growth models. Computational Management Science 5 (1), 95–117.

Bosetti, V., Carraro, C., Tavoni, M., 2009. A chinese commitment to commit: can it break the negotiation stall? Climatic Change 97, 297–303, 10.1007/s10584-009-9726-8. http://dx.doi.org/10.1007/s10584-009-9726-8

Calvin, K., 2011. AME Synthesis. this issue.

Calvin, K., Edmonds, J., Bond-Lamberty, B., Clarke, L., Kim, S. H., Kyle, P., Smith, S. J., Thomson, A., Wise, M., Dec. 2009. 2.6: Limiting climate change to 450 ppm co2 equivalent in the 21st century. Energy Economics 31 (Supplement 2), S107–S120.

Chen, W., May 2005. The costs of mitigating carbon emissions in china: findings from China MARKAL-MACRO modeling. Energy Policy 33 (7), 885–896. http://www.sciencedirect.com/science/article/pii/S030142150300315X

Chen, W. Y., Wu, Z. X., He, J. K., Gao, P. F., Xu, S. F., Jan. 2007. Carbon emission control strategies for china: A comparative study with partial and general equilibrium versions of the china markal model. Energy 32 (1), 59–72.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M., 2009. International climate policy architectures: Overview of the EMF-22 international scenarios. Energy Economics 31 (Supplement 2), S64 – S81, international, U.S. and E.U. Climate Change Control Scenarios: Results from EMF 22.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Château, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magné, B., Scrieciu, S., Turton, H., van Vuuren, D. P., 2010. The economics of low stabilization: Model comparison of mitigation strategies and costs. The Energy Journal 31.

Edmonds, J., Wilson, T., Rosenzweig, R., 2000. A Global Energy Technology Strategy Project Addressing Climate Change: An Initial Report an International Public-Private Collaboration. Joint Global Change Research Institute, College Park, MD. http://www.globalchange.umd.edu/data/gtsp/docs/GTSP-indfind.pdf

EPRI, 2007. The Power to Reduce CO2 Emissions ? The Full Portfolio. EPRI Discussion Paper Palo Alto, CA. http://mydocs.epri.com/docs/CorporateDocuments/AboutEPRI/DiscussionPaper2007.pdf

Fisher, B., Nakicenovic, N., K. Alfsen, J. C. M., de la Chesnaye, F., Hourcade, J.-C., Jiang, K., Kainuma, M., Rovere, E. L., Matysek, A., Rana, A., Riahi, K., Richels, R., Rose, S., van Vuuren, D., Warren, R., 2007. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, Ch. Issues related to mitigation in the long term context.

IEA, 2007. Energy Balances of non-OECD Countries. International Energy Agency, Paris.

IEA, 2007. Energy Balances of OECD Countries. International Energy Agency, Paris.

IEA, 2010. World Energy Outlook 2010. International Energy Agency, Paris.

IPCC, 2007. Climate change 2007: Synthesis report. Tech. rep., Intergovernmental Panel on Climate Change. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf

IPCC, 2011. Special Report Renewable Energy Sources and Climate Change Mitigation. Intergovernmental Panel on Climate Change, Cambridge University Press.

Jakob, M., Luderer, G., Steckel, J., Tavoni, M., Monjon, S., ???? Time to act now? assessing the costs of delaying climate measures and benefits of early action. Climatic Change, 1–2110.1007/s10584-011-0128-3. http://dx.doi.org/10.1007/s10584-011-0128-3

Jiang, K., Hu, X., 2006. Energy demand and emissions in 2030 in china : scenarios and policy options. Environmental economics and policy studies 7, 233–250.

Jiang, K., Masui, T., Morita, T., Matsuoka, Y., Feb. 2000. Long-term ghg emission scenarios for asia-pacific and the world. Technological Forecasting and Social Change 63 (2-3), 207–229. http://www.sciencedirect.com/science/article/pii/S0040162599001109

Kainuma, M., Matsuoka, Y., Morita, T. (Eds.), 2003. Asia-Pacific Integrated Modeling. Springer, Tokyo.

Knopf, B., Luderer, G., Edenhofer, O., 2012. Exploring the feasibility of low stabilization target. WIREs Clim Change 1, DOI: 10.1002/wcc.124.

Krey, V., Clarke, L., 2011. Role of renewable energy in climate mitigation: a synthesis of recent scenarios. Climate Policy DOI: 10.1080/14693062.2011.579308.

Krey, V., Riahi, K., Dec. 2009. Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets–greenhouse gas mitigation scenarios for the 21st century. Energy Economics 31 (Supplement 2), S94–S106. http://www.sciencedirect.com/science/article/pii/S0140988309001170

Leimbach, M., Bauer, N., Baumstark, L., Edenhofer, O., 2010. Mitigation costs in a globalized world: Climate policy analysis with REMIND-R. Environmental Modeling and Assessment 15, 155–173, 10.1007/s10666-009-9204-8.

Lightfoot, H. D., Aug. 2007. Understand the three different scales for measuring primary energy and avoid errors. Energy 32 (8), 1478–1483.

Luderer, G., Bosetti, V., Jakob, M., Leimbach, M., Steckel, J., Waisman, H., Edenhofer, O., 2012. The economics of decarbonizing the energy system - results and insights from the RECIPE model intercomparison. Climatic Change, DOI 10.1007/s10584-011-0105-x.

Luderer, G., Leimbach, M., Bauer, N., Kriegler, E., 2010. Description of the ReMIND-R model. Technical Report, Potsdam Institute for Climate Impact Research. http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/models/remind/REMIND_Description_June2010_final.pdf

Macknick, J., 2011. Energy and co2 emission data uncertainties. Carbon Management 2(2), 189–205.

Manne, A., Mendelsohn, R., Richels, R., Jan. 1995. Merge : A model for evaluating regional and global effects of ghg reduction policies. Energy Policy 23 (1), 17–34. http://www.sciencedirect.com/science/article/pii/030142159590763W

McKinsey & Company, 2009. Pathways to a low carbon economy – version 2 of the global greenhouse gas abatement cost curve. Tech. rep., McKinsey & Company. https://solutions.mckinsey.com/ClimateDesk/default.aspx

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J., Allen, M. R., Apr. 2009. Greenhouse-gas emission targets for limiting global warming to 2°c. Nature 458 (7242), 1158–1162.

NEA, 2009. Uranium 2003: Resources, production and demand. Tech. rep., Nuclear Energy Agency.

Nordhaus, W., Nakicenovic, N. (Eds.), 2011. Special Issue on The Economics of Technologies to Combat Global Warming. Energy Economics, Volume 33, Issue 4.

Nordhaus, W. D., Yang, Z., Sep. 1996. A regional dynamic general-equilibrium model of alternative climate-change strategies. The American Economic Review 86 (4), 741–765.

Placet, M., Humphreys, K., Mahasenan, N. M., 2004. Climate Change Technology Scenarios: Energy, Emissions and Economic Implications. Pacific Northwest National Laboratory, Richland, Washington,.

Raupach, M. R., Marland, G., Ciais, P., Le Quere, C., Canadell, J. G., Klepper, G., Field, C. B., Jun. 2007. Global and regional drivers of accelerating co2 emissions. Proceedings of the National Academy of Sciences 104 (24), 10288–10293.

Riahi, K., Grübler, A., Nakicenovic, N., Sep. 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change 74 (7), 887–935.

Riahi, K., Roehrl, R. A., 2000. Greenhouse gas emissions in a dynamics-as-usual scenario of economic and energy development. Technological Forecasting and Social Change 63 (2-3), 175 – 205. doi: 10.1016/S0040-1625(99)00111-0

Richels, R., Blanford, G., Rutherford, T., 2009. International climate policy: a "second best" solution for a "second best" world? Climatic Change 97, 289–296, 10.1007/s10584-009-9730-z. http://dx.doi.org/10.1007/s10584-009-9730-z

Shukla, P. R., Dhar, S., Mahapatra, D., 2008. Low-carbon society scenarios for india. Climate Policy Volume 8, Supplement 1, S156–S176(21).

Steckel, J. C., Jakob, M., Marschinski, R., Luderer, G., Jun. 2011. From carbonization to decarbonization?–past trends and future scenarios for china’s co2 emissions. Energy Policy 39 (6), 3443–3455.

Trieb, F., Schillings, C., O’Sullivan, M., Pregger, T., Hoyer-Klick, C., 2009. Global potential of concentrating solar power. Conference Proceedings, SolarPACES 2009. http://www.dlr.de/tt/en/Portaldata/41/Resources/dokumente/institut/system/projects/reaccess/DNI-Atlas-SP-Berlin_20090915-04-Final-Colour.pdf

van Vuuren, D., den Elzen, M., Lucas, P., Eickhout, B., Strengers, B., van Ruijven, B., Wonink, S., van Houdt, R., 2007. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Climatic Change 81, 119–159.